Evaluating Response Planning Initiatives: Modeling Assumptions

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Abstract

The potential for intentional contamination of the nation's drinking water infrastructure has heightened utility awareness regarding distribution system security. Corrective actions implemented by a water utility following a contamination incident have the potential to significantly mitigate public health and infrastructure impacts. Many mitigation and response options are available (e.g., flushing at hydrants to remove contaminants from pipes, injecting disinfectant or decontamination agents at booster stations to treat the water or remove the contaminant from pipe walls, sampling at locations throughout the network to determine the extent of contamination, or instituting "Do Not Drink" or "Do Not Use" public advisories). For any given utility, some options might be more effective than others, and the effectiveness might depend on timing and other factors. Modeling and simulation studies can help utility decision-makers evaluate the effectiveness and feasibility of various response actions. However, utilities need to use realistic input parameters to ensure that modeling results are meaningful.

This paper summarizes the input parameters needed to realistically model utility response options as well as lessons learned from discussions with two water utilities on the practicality of initiating specific response actions. The purpose of the utility discussions was to ground-truth modeling assumptions and eliminate impractical and inefficient response options, while also placing realistic bounds on input parameters. With more accurate information, the results from simulation and optimization models will be more acceptable to water utilities and policy makers. Generating plausible approaches to dealing with a contamination incident will support the utilities' decision making process and facilitate selection of the most effective operational response. The value of this type of response planning is discussed for a wide audience of water utilities.

Introduction

As one of the nation's critical infrastructures, drinking water distribution systems are susceptible to contaminant intrusion, whether accidental or intentional. The prospect of contamination of the nation's drinking water infrastructure has heightened awareness regarding protection of drinking water distribution systems, and also increased research on minimizing and mitigating threats. Contaminants in the distribution system can be detected by a Contamination Warning System (CWS) that includes optimally placed water quality sensors, rapid communication, data analysis, and confirmatory sampling (Janke et al. 2006; Murray et al. 2008). Decreases in public health and infrastructure damages, as well as an increase in utility rapid response potential can be attributed to the implementation of a CWS. Recent analysis of nine large water utilities has estimated that a significant reduction in public health impacts (48%) with an associated economic impact savings of over $19 billion can be achieved with application of a CWS (Murray et al. 2009).

The online monitoring component of a CWS is comprised of sensors that evaluate continuous water quality. Event detection systems (EDSs), such as the open source CANARY program (Hart et al. 2009), can be utilized to distinguish outliers in water quality data, which vary from typically observed values by more than a designated threshold. Free chlorine sensors are one of the most critical components of a CWS because inconsistencies from baseline measurements or an abrupt decrease in residual concentration might be indicative of some form of contaminant intrusion (Hall et al. 2007).

In the event that an anomalous water quality incident is detected in the distribution system, utility response actions would likely follow a consequence management plan where the presence of contamination would be confirmed, crews would be mobilized to respond, and mitigation actions would be enacted. The explicit mitigation strategy employed would be utility-specific and dependent on an existing knowledge of the distribution systems hydraulics and demand patterns.

An assortment of response strategies (e.g., flushing, valve closures, storage tank isolation, and booster disinfection) are examined in this paper, as consequence management involves application of more than one mitigation technique. A properly designed flushing action can dislodge and transport contaminants out of the distribution system. Valve isolation, which can be used to segregate contaminated pipe(s) from the rest of the distribution system, can contain and control the spread of a contaminant. Storage tank isolation can be used to prevent contaminated water from entering the tank inflow, or it can be used to confine the contaminant within the tank and retain it until suitable decontamination measures can be taken. Employing booster disinfection can treat specific portions of the distribution network in order to mitigate the effects of contaminant agents, and also presents a potential means for introducing alternative decontaminant agents (e.g., surfactants or pH-modification agents) into the distribution system. Public advisories, such as instituting “Do Not Drink” notifications, are a critical response to a contamination and are explored further in this work.

Modeling and simulation studies are invaluable tools in response planning. Many details pertaining to treatment and decontamination, specifically about when, where, how, and for how long can be studied ahead of time using modeling and simulation. Examining various response scenarios through modeling can provide an effective proving ground for utilities without having to experience, for example, that implementing flushing in a given scenario causes the contamination to spread further in the network.

In order to address the objective of this work, information on realistic modeling input parameters for specific response actions was obtained through collaboration with two large drinking water utilities. The data obtained from the utilities aided in placing more precise bounds on response options by identifying the most realistic response parameters achievable (e.g., flushing rates, or the total number of booster stations that can be placed in a network). This effort is part of a larger work to establish a viable water security response planning tool for utilities.

Flushing

Flushing is a common method utilities use to address water quality concerns. It is a response option that can be undertaken relatively quickly after an event, and be made even more efficient through careful selection of the most advantageous flushing locations, rates, and durations.

Utilities make use of two common flushing routines, conventional and unidirectional, to manage water quality issues within the distribution system. Conventional flushing, practiced by the majority of utilities, involves opening one or more hydrants in an area of the distribution system experiencing water quality concerns until water quality standards (e.g., restoration of an acceptable disinfectant residual, reduction in unpleasant taste or odor) are met (AwwaRF 2003b). With conventional flushing, velocities may not be maximized, given that hydrants may not be opened in sequential manner. In comparison, the unidirectional flushing technique incorporates valve closures and opens hydrants in a sequential manner, so that water is only flushed in one direction, maximizing velocity and cleaning efficiency.

Modeling and simulation of flushing allows for an examination of the utility-controlled options, such as where to flush, for how long, and at what rate. An optimization tool linked with a hydraulic/water quality model can be utilized to select the most beneficial hydrant flushing locations (Haxton and Uber 2010). Baranowski et al. (2008) examined the effects of simulated flushing, valve closures, and a combination of both to reduce contamination spread in an example distribution network. Each operational response was evaluated with regard to its mitigation capability, in order to determine the practicality of implementing various operational responses that a utility could use in the event of a real-time contamination.

Although modeling and simulation of response options can provide information on the benefits of various mitigation scenarios, the accuracy of the modeling results can be improved if real-world constraints are placed on input parameters. This may not be possible without the development of a comprehensive database that utilities can turn to when they need guidance for response protocol. Given that no such database of response protocols currently exists, many operational variables are approximated (AwwaRF 2003b). Moreover, this type of information may be difficult to come by since it is likely utility-specific. Baranowski et al. (2008a) obtained information on flushing and valve closure parameters from Ann Arbor's water treatment plant personnel. Input parameters obtained in this study included minimum and maximum values associated with:

- The practiced flushing rate in gallons per minute (gpm)
- The flushing duration (hours or minutes)
- The maximum number of hydrants that can be flushed simultaneously without causing depressurization
- The response time for flushing crews from time of detection to initiation of flushing

Booster Disinfection

Injecting disinfectant directly into the distribution system through a booster station is another viable consequence management option for utilities. Booster disinfection is a technique utilized within a drinking water distribution system in which a disinfectant is applied at predetermined locations throughout the network. This can be done at a booster pump station, valve vault, or pressure reducing station, provided there is electricity available to run the small injector pump for the injection (Satterfield 2006). Employing disinfectant booster stations within a drinking water distribution system in conjunction with conventional treatment plant practices can meet residual requirements at all points of consumption without releasing disproportionate concentrations of disinfectant at the point of entry into the system (AwwaRF 2003a). Additionally, modeling and simulation of booster disinfection has shown the potential for a reduction in the total mass of disinfectant added to the system by carefully selecting the booster locations (Boccelli et al. 1998; Tryby et al. 2002; AwwaRF 2003a; Propato and Uber 2004). More recent modeling efforts have focused on applying booster disinfection in the context of response to a contamination incident (Haxton et al. 2011).

Under normal operations, booster chlorination addresses the issue of maintaining an adequate disinfectant residual throughout a distribution system, which is a requirement enforced under the Surface Water Treatment Rule (SWTR). Under the SWTR, finished water leaving the water treatment plant cannot drop below the 0.2 mg/L disinfectant residual benchmark for more than a four hour period without falling out of compliance (US EPA 1990). Sustaining a detectable residual throughout the distribution system is another requirement under SWTR. However, this mandate creates a major challenge for utilities, who must balance meeting the treatment objective of providing an adequate disinfectant residual with minimizing potential public health risks from elevated concentrations of disinfectant and associated by-products. Booster chlorination can resolve these concerns through the reapplication of disinfectant at strategic points in the distribution system. It can also be employed for consequence managment in addition to conventional use. Following a contamination event, chlorination via multiple booster stations can be used to treat the contaminant in the pipes.

In a typical booster station, the concentration of chlorine is measured both at the inlet and outlet of the booster station. As the chlorine residual enters the booster station, the analyzer at the inlet reads the measurement and controls the chlorine injection rate to attain the desired residual value downstream of the booster station. Injection dosages of the booster disinfectant are applied manually, by a human operator, or are automated and controlled remotely via a Supervisory Control and Data Acquisition (SCADA) system. In the case of automated control, the chemical feed pumps are monitored remotely at the water treatment plant. The feed pumps can also be equipped with an alarm, which detects a malfunction in the pump operation, such as a loss of chemical feed (Potts 2001).

The chemical feed rate for the disinfectant injection can be either flow-paced, meaning it is adjusted based on measurements of control variables such as the flow rate, or it can be constant. In order to maintain a system-wide chlorine residual of 1.0 mg/L, typical feed rates vary between 1.0-2.0 mg/L (US EPA 1999; AMWA 2007). An AWWA survey (2003a) of water utilities operating booster stations shows that most (55 %) used a constant delivery dose, while 35 % used flow-pacing or residual pacing to adjust the dose. A few stations used a time-dependent set-point control. The water flow not only affects the quantity of the chlorine dose, but also the type of dosing equipment that is most suitable (Potts 2001).

A key consideration for implementing booster disinfection is the proper placement of booster facilities in the distribution system. Kirmeyer et al. (2000) distinguished the following criteria in selecting the most beneficial location of booster stations: the water to be treated travels in one direction, the residual concentration exhibits a decrease but is not completely absent, and a relativley large volume of water can be disinfected by the booster station. According to Kirkmeyer, these conditions can be met when the booster station is positioned in an existing pump station or at the outlet of a storage facility where metering equipment is already located.

The type of disinfectant used at a booster facility can be a critical safety issue for utilities. Although a 2008 AwwaRF suvey indicated that the majority of responding utilities (63%) disinfected with chlorine gas (AwwaRF 2008), similar to the 2003 AwwaRF survey, a number of utilities are converting from chlorine gas to sodium hypochlorite as a preferred method of disinfection (AMWA 2007). For example, the Northern Kentucky Water District previously operated four chlorine booster disinfection stations in order to maintain a system chlorine residual of 1.0 mg/L. Of the four booster stations, two are located in residential areas. Following an accidental release from one of the residential booster stations, the utility made the decision to convert from the use of chlorine gas to liquid sodium hypochlorite for safety purposes (AMWA 2007).

Optimization of the quantity, locations, and general operation of disinfectant booster stations can be achieved through modeling and simulation. When modeling booster disinfection as a contamination response option, particular input parameters are required. These input parameters include design details, such as the total number of booster stations that can be placed within a distribution system without restrictions. Operational information is also required for modeling inputs. Data on the choice of disinfectants utilized at booster stations as well as specifics on feed control processes are critical for modeling and simulation studies.

Additional Response Strategies

As part of the larger water security tool to evaluate mitigation strategies for utilities, research on additional response approaches has been and will be conducted. Research includes the study of source inversion methods (Shang et al. 2001; Laird et al. 2006) to identify the location where a contaminant was introduced into the network using real-time sensor signals as input. Additional research includes studies to identify optimal confirmatory distribution system sampling locations to categorize where and when elevated levels of a contaminant are detected in the water; determine valve and storage tank isolation strategies to prevent contamination from entering a tank or high customer demand node (Baranowski et al. 2008a; Baranowski and Leboeuf 2008b; Hagar et al. 2011); develop risk maps to identify regions in which people might have been exposed to elevated contaminant concentrations; and develop real-time hydraulic and water quality modeling packages to more accurately reflect water distribution dynamics (Hatchett et al. 2011). When all of the potential response approaches are combined, they will provide practical consequence management assistance for utilities.

Approach

A background literature review on flushing and booster disinfection was completed in order to obtain information regarding realistic response strategies. A number of questions concerning the response strategies remained following the literature review. These remaining questions underscored the need for collaboration with drinking water utilities in order to gain insight on realistic operational parameters for use in modeling and simulation of the response options. For this study, two drinking water utilities were selected to provide utility-specific response information.

The following questions illustrate what was asked of the utilities to facilitate booster station modeling:

- How many booster stations are present in the distribution system?
- How often are they run/operated? Continuously? On a set schedule? Seasonally?
- How is the chlorine dosage controlled at the stations? Flow paced? Constant mass rate? Based on chlorine residual measurements? What is the average chlorine dosage?
- How are they operated? Automatically via SCADA? Manually? How long does it take to turn on/off a booster station?
- How were the locations of the stations determined? Do they need to be located near certain pieces of equipment? Near a tank or pump?

Baranowski et al. (2008a) previously collaborated with the City of Ann Arbor on the subject of flushing and valve closure as a response to a contamination incident. The subsequent list of questions was asked of the utility in regard to their flushing practices. Identical questions were asked of the two utilities involved in this current work for purposes of evaluation.

- What is the total number of hydrants present within the distribution system?
- Are hydrants exercised, if so how often?
- What are the achievable flows out of a hydrant?
- What is the total number of in-line valves?
- Where are isolation valves located?
- Do all pipes have isolation valves?
- Is a flushing program practiced? What type (conventional or unidirectional)?
- Is continuous service provided to customers during flushing?
- If unidirectional flushing is practiced, how are hydrants and valves determined and used?
- What is the practiced flushing rate (gpm)?
- How long is this rate maintained (hours or minutes)?
- What is the size range of pipes flushed (___ to ___ inches)?

Results and Discussion

Results of discussions with utilities regarding practical limitations on booster disinfection, flushing, and valve isolation will be discussed at the EWRI congress in May 2012.

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